



Radiocarbon on Titan

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Abstract—We explore the likely production and fate of ¹⁴C in the thick nitrogen atmosphere of Saturn's moon Titan and investigate the constraints that measurements of ¹⁴C might place on Titan's photochemical, atmospheric transport and surface-atmosphere interaction processes. Titan's atmosphere is thick enough that cosmic-ray flux limits the production of ¹⁴C: absence of a strong magnetic field and the increased distance from the Sun suggest production rates of ~9 atom/cm²/s, ~4× higher than Earth. The fate and detectability of ¹⁴C depends on the chemical species into which it is incorporated: as methane it would be hopelessly diluted even in only the atmosphere. However, in the more likely case that the ¹⁴C attaches to the haze that rains out onto the surface (as tholin, HCN or acetylene and their polymers), haze in the atmosphere or recently deposited on the surface would be quite radioactive. Such radioactivity may lead to a significant enhancement in the electrical conductivity of the atmosphere which will be measured by the Huygens probe. Measurements with simple detectors on future missions could place useful constraints on the mass deposition rates of photochemical material on the surface and identify locations where surface deposits of such material are "freshest".

INTRODUCTION

The most widely known radiochronometer is undoubtedly ¹⁴C, whose half-life (5570 years) and geochemistry make it uniquely suited to dating events in the terrestrial biosphere during human history and recent pre-history. It is probably the only isotope with an entire journal devoted to it (*Radiocarbon*). On the other hand, its half-life is too short to measure most extraterrestrial processes of interest. Coupled with the rarity of organic chemistry in the solar system, the only spacecraft measurements of ¹⁴C have been as an artificial tracer in the *Viking* biology experiments on Mars.

However, there is one solar system body, Saturn's giant moon Titan, where conditions are right for its production and for its measurements, and where organic chemistry may be occurring on timescales such that its measurement would be scientifically useful.

On Earth, hot ¹⁴C atoms are produced by the interaction of galactic cosmic rays (GCRs) with nitrogen atoms in the atmosphere. These hot carbon atoms are assumed to combine with oxygen, yielding carbon monoxide, which is rapidly oxidized into carbon dioxide. That in turn is respired by living things to incorporate an equilibrium concentration of radioactive carbon. After death, the concentration of ¹⁴C drops due to decay, and thus the intrinsic ¹⁴C radioactivity of living matter acts as a measure of age.

Titan, to be the object of close scrutiny of the NASA–ESA Cassini–Huygens mission to arrive in 2004, also has a thick nitrogen atmosphere, which therefore should also produce ¹⁴C by GCR interaction. Although living things are not expected on Titan, the incorporation of radiocarbon into the abundant organic inventory, on the surface and the atmosphere, may provide a useful tracer on the processes by which those organic materials are formed and transported. Furthermore, the low background radioactivity eliminates some difficulties in measurements, although the low temperature (~95 K at the surface) and great distance from Earth (~10 AU) will still make its measurement a technical challenge.

In this paper, we first briefly summarize the radiocarbon production on Earth and the size of the carbon reservoirs, to place Titan in context. We then determine the likely production on Titan, taking into account its different setting in the solar system and consider the likely chemical fate of ¹⁴C, since oxidation into carbon dioxide is unlikely in Titan's heavily reducing atmosphere. The inventories, photochemical production rates and transport times of the different candidate species are then considered, and thus the likely concentrations of radiocarbon established, a parameter which varies dramatically with the sink species. Finally, we consider how the ¹⁴C abundance in different reservoirs on Titan might be measured and the constraints such measurements might place on the geochemical cycles on Titan.

Carbon-14 on Earth

The average terrestrial production rate, P , is generally estimated at ~ 2.02 atoms $\text{cm}^{-2} \text{s}^{-1}$ (Masarik and Beer, 1999), to ~ 2.2 $\text{cm}^{-2} \text{s}^{-1}$ (Damon and Sternberg, 1989). Although modelling calculations tend towards the lower value, there is good reason to assume the average over a solar cycle of $\sim 2.2 \pm 0.2$ is a good estimate (Damon and Sternberg, 1989). The value of 2.2 $\text{cm}^{-2} \text{s}^{-1}$ may be expressed as 6.8×10^{11} $\text{m}^{-2} \text{year}^{-1}$ or 1.6×10^{-14} $\text{kg m}^{-2} \text{year}^{-1}$. The half-life ($t_{1/2}$) of ^{14}C is 5568 ± 30 years, and thus the decay constant λ is 1.2×10^{-4} year^{-1} . In order to balance the production rate of 6.8×10^{11} $\text{m}^{-2} \text{year}^{-1}$ there must therefore be the same area density of decays, requiring an area density of ^{14}C atoms of P/λ or 5.7×10^{14} atoms m^{-2} . This equilibrium concentration may be expressed as 1.3×10^{-11} kg m^{-2} and compared with the carbon (mostly ^{12}C , with 1.11% ^{13}C) reservoirs in the atmosphere (1.5 kg m^{-2}), land biosphere (1.2 kg m^{-2}), soil and detritus (3.1 kg m^{-2}), surface ocean (2.0 kg m^{-2}), deep ocean (75 kg m^{-2}), and fossil carbon and carbonates (500 kg m^{-2}) (Siegenthaler and Sarmiento, 1993; Houghton *et al.*, 1996).

In the atmosphere, and in reservoirs that exchange carbon (as CO_2) with the atmosphere on timescales short compared with the half-life, ^{14}C therefore has an abundance equal to the ratio of the equilibrium concentration to the size of the exchanging reservoir (adding relevant terms above, ~ 10 kg m^{-2}). The current atmospheric pre-bomb level is then $\sim 1.2 \times 10^{-12}$. In terms of activity this is a decay rate of 13.6 dpm/g C (decays per minute per gram of carbon). ^{14}C undergoes β -decay, with an energy of 0.158 MeV.

TITAN'S ATMOSPHERE

Titan, with a radius of 2575 km, is the largest satellite of Saturn and the second-largest satellite in the solar system. Titan has the remarkable distinction of being the only satellite with a significant atmosphere (*e.g.*, Coustenis and Taylor, 1999; Lorenz and Mitton, 2002). Despite its small size, it has a predominantly nitrogen atmosphere with a surface pressure of 1.5 bar and a temperature of 94 K. Since the surface pressure is simply the weight per unit area of the gas, Titan's low surface gravitational acceleration of 1.35 m s^{-2} requires that the column mass of gas is $\sim 10\times$ higher on Earth.

A minor ($\sim 2\%$) constituent in the atmosphere is methane, which plays a role analogous to water on Earth. It is a condensible greenhouse gas and probably takes part in an active (although gentle, given the feeble sunlight at 9 AU from the Sun) hydrological cycle of clouds, precipitation and surface reservoirs and flows.

Methane is irreversibly destroyed by photolysis in the upper atmosphere, yielding ethane, acetylene and a host of other organic species. Ethane is a liquid at Titan's surface temperatures, and may have accumulated to kilometer depths over geologic time (Lunine *et al.*, 1983). The more refractory

of the photolysis products form an optically-thick haze in the atmosphere that has so far prevented close study of Titan's landscape by spacecraft, although visibility improves in the near-infrared. This haze absorbs sunlight, and warms the stratosphere (see Fig. 1) in a manner similar to ozone on Earth. The drop in temperature towards the tropopause leads to condensation of many organic species (*e.g.*, Sagan and Thompson, 1984) as they diffuse downward from their sites of production.

Thus Titan has a complicated surface-atmosphere system, the complex evolution of which is already being hinted at by remote determinations of carbon and nitrogen isotopes (Lunine *et al.*, 1999). Many aspects of the atmospheric photochemistry and at least a glimpse of its landscape will be revealed by the NASA-ESA Cassini-Huygens mission, which will arrive in 2004 and study Titan for 4 years from orbit with infrared and ultraviolet spectroscopy, imaging, radar and direct sampling of the upper atmosphere. Additionally, in early 2005 a parachute-borne probe will make a 2.5 h descent through the atmosphere, making *in situ* investigations.

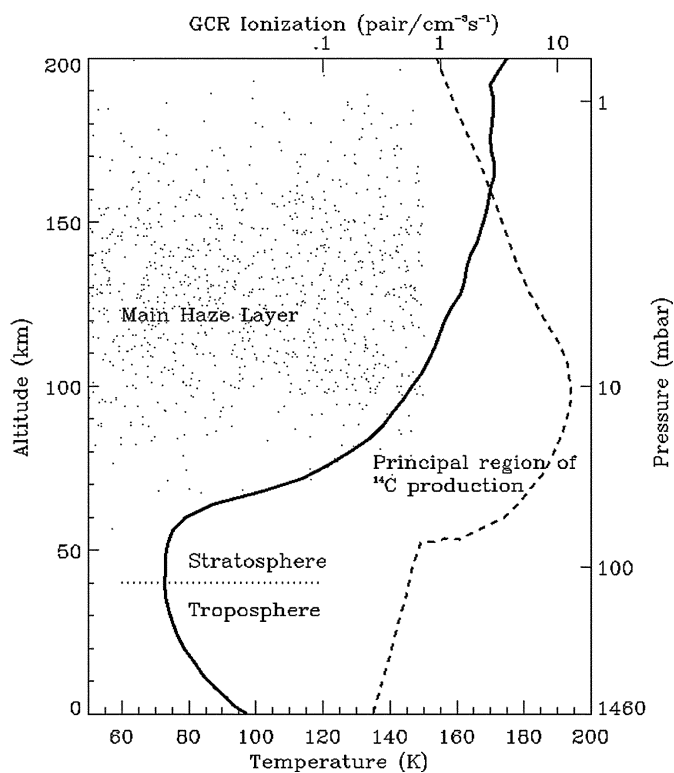


FIG. 1. The vertical temperature structure of Titan's atmosphere (solid line, lower scale). Note in particular the steep drop in temperature from 150 km down to ~ 50 km—this leads to the condensation of many organic species, including those likely to carry ^{14}C . Upper scale and dashed line shows ionization due to cosmic rays from Borucki *et al.* (1987)— ^{14}C production will have a profile similar in shape (although in magnitude much smaller), with most production above 70 km.

It seems likely that future foci for Titan studies may center on its meteorology, and on the possible interaction of ephemeral exposures of liquid water (Lorenz *et al.*, 2001) with the organics that accumulate on its surface. This interaction is likely to yield amino acids and other compounds of astrobiological interest. In this paper we show that study of ^{14}C may help understand the accumulation processes of organics on Titan's surface.

PRODUCTION OF CARBON-14 ON TITAN

We take a terrestrial production rate of ^{14}C of 2.2 atoms $\text{cm}^{-2} \text{s}^{-1}$ as our starting point. A first correction is due to the absence of a significant magnetic field at Titan. Masarik and Beer (1999) estimated that were it not for the Earth's magnetic field, the production rate would be about a factor of 2 higher, 4.5 $\text{cm}^{-2} \text{s}^{-1}$.

The galactic cosmic-ray flux, and hence the ^{14}C production rate is modulated by solar activity. This occurs because the cosmic rays (heavy charged nuclei) are affected by the magnetic field convected outward from the Sun by the solar wind (see, for example, Jokipii, 1991). There is therefore an anticorrelation between solar activity and observed cosmic-ray flux.

The dependence is expressed as a solar modulation parameter (sometimes written as ϕ , sometimes as MV) which varies from as much as 1000–1200 (solar maximum average is 900) to ~400 (solar minimum) over the last few solar cycles, with the ^{14}C production rate from solar maximum to solar minimum varying by a factor of ~1.46. However, over longer periods (thousands of years) the modulation parameter can fall to zero (*e.g.*, during the Maunder minimum)—see, for example, O'Brien *et al.* (1991).

If we assume a modulation parameter of near zero for Titan (since the solar wind will drop by a factor of ~100 at Saturn's distance from the Sun), the production rate will be increased by a factor of ~2 (Table 3 in O'Brien *et al.*, 1991). (The enhancement factor is only ~1.4 for a geomagnetic field strength equal to the present terrestrial value, but increases for lower fields.) The combination of low geomagnetic field and low modulation parameter by those authors gives an enhancement of ~3.6.

A final correction factor is that an incoming cosmic ray has a probability of only ~78% of striking a nitrogen atom in the Earth's atmosphere, since oxygen makes up a significant fraction of the atmosphere. On Titan, with ~98% N_2 , the probability of encountering a nitrogen atom and thus forming a ^{14}C atom is thus increased by a further factor $0.98/0.78 = 1.25$. We therefore predict that the production rate of radiocarbon on Titan is therefore 4.5× higher than on Earth, or ~9 atoms $\text{cm}^{-2} \text{s}^{-1}$.

The majority of ^{14}C production occurs above a mass density level in the atmosphere of ~2000 kg m^{-2} (*i.e.*, ~200 mbar on Earth, or 25 mbar on Titan, at altitudes of 12 and 70 km, respectively). The production rate at 6000 kg m^{-2} is a factor of 100 less than the peak production at the top of the atmosphere (Masarik and Beer, 1999), so we may neglect any production

at altitudes lower than the levels quoted above. Although rather higher than for Earth, the 70 km altitude on Titan is sufficiently low that the production rate is not augmented by a geometric factor (*i.e.*, the atmosphere's GCR capture cross section is not significantly larger than that of the solid body—the same is not true, for example, for extreme ultraviolet light which is intercepted at considerably higher altitudes on Titan). Figure 1 shows a profile of ionization due to GCRs from Borucki *et al.* (1987) which will mirror the radiocarbon production—production falls below 90 km or so as the flux becomes attenuated (see also discussion of GCR-induced N_2 chemical dissociation in Capone *et al.*, 1983).

THE FATE OF CARBON-14 ON TITAN

The strong affinity of molecular oxygen for organic material on Earth makes it straightforward to assume the sink species for radiocarbon produced in the atmosphere. Titan's reduced atmosphere makes the chemical fate of ^{14}C less obvious. We consider four distinct possibilities.

One is as methane, the dominant carbon-bearing species in the Titan atmosphere. This could conceivably be formed by the interaction of hot ^{14}C atoms with methane and or hydrogen (present at ~0.1%). However, the relatively low abundance of these species compared with nitrogen, and the simple hydrogen balance, suggests this is unlikely. Another sink as a possible product of ^{14}C interaction with methane is as ethane or ethene. Ethane is the dominant photochemical sink for carbon in Titan's atmosphere.

However, the most likely molecule which hot ^{14}C atoms would hit is nitrogen, and we thus consider it most likely that HCN is then the principal sink of ^{14}C . The final possibility is as "haze". ^{14}C atoms may combine in a heterogenous fashion (perhaps only a physical rather than chemical attachment) with existing aerosol particles, much as ions are absorbed by smoke particles in the terrestrial atmosphere. ^{14}C interaction with methane may also yield acetylene, which either as frost or a polymer may contribute to the aerosol. For the purpose of this paper, we consider all solid material to be equivalent, and thus the physical attachment process and chemical incorporation in acetylene and tholin are lumped together.

Note that, as argued in Lara *et al.* (1999), haze may be a significant sink of HCN in Titan's atmosphere: when transport and condensation are the only sinks for HCN in photochemical models, the HCN abundance is found to be higher than indicated by observations when the eddy diffusion coefficient is set to a value that allows the hydrocarbon abundances to be consistent with observations. Thus another HCN sink is required, assuming the hydrocarbon and nitrile photochemical schemes themselves are correct. An HCN "polymerization" and incorporation into the haze seems to provide acceptable results. Thus any radiocarbon HCN production may in large part be eventually absorbed into the haze. These processes are summarized in Fig. 2.

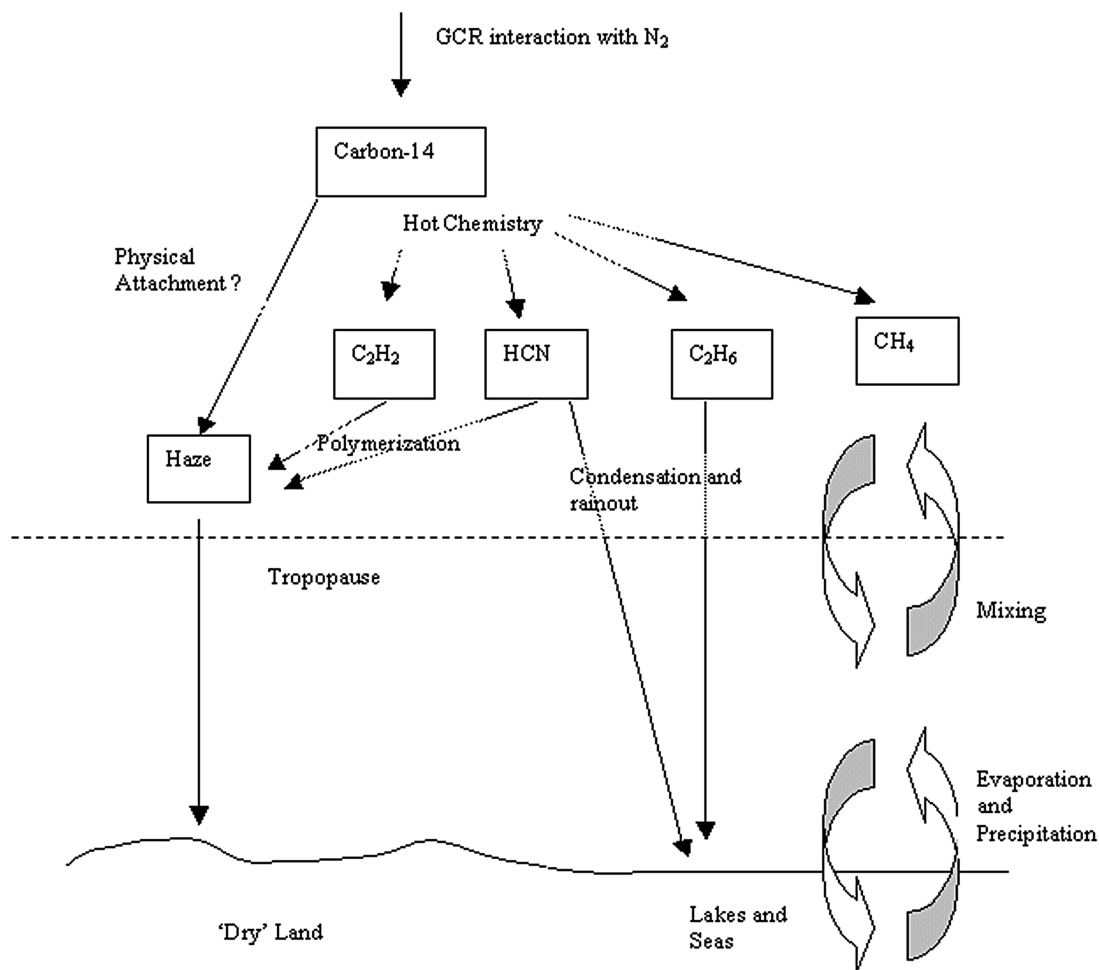


FIG. 2. Schematic of the carbon "cycle" on Titan and the fluxes of different chemical species.

CARBON RESERVOIRS ON TITAN

The carbon reservoirs on Titan are summarized in Table 1, using data from McKay *et al.* (2001), Yung *et al.* (1984), Toubanc *et al.* (1995) and Lara *et al.* (1996). The reservoirs may be divided in two dimensions, vertically and by chemical composition. In the vertical dimension, we may consider the stratosphere (altitudes above 40 km), the troposphere, and the surface. Virtually all the ¹⁴C is produced in the stratosphere (see earlier). Although as we show in the next section, the stratosphere and troposphere are mixed on relatively short timescales (and thus might be considered together as simply the "atmosphere" as on Earth), we call them out separately because several of the likely sink species are much more abundant in the warmer stratosphere than in the cold troposphere which they transit briefly as condensed droplets.

There may be additional vertical segmentation, analogous to the near-surface mixed layer and stagnant deep ocean on Earth. In the interests of simplicity, and since deep reservoirs are unlikely to be accessible to instrumentation, we consider

only one vertical surface reservoir. As in the atmosphere, the different carbon-bearing species may be thermally, mechanically or chemically separable.

It is known from analyses of near-infrared spectra that the lower atmosphere of Titan is relatively clear of haze. We therefore neglect any tropospheric reservoir of solid material and assume that haze is deposited directly on the surface after removal from the stratosphere.

HCN—present as a trace in the stratosphere—is removed by condensation (and possibly incorporation into solid haze material) and is ultimately deposited on the surface as a liquid. Again, it is assumed that this compound has a negligible abundance in the troposphere, where its vapor pressure is very low. C₂H₆ is similarly removed by condensation, although its vapor pressure is higher. The C₂H₆ production by photochemistry is around 30× higher than that of HCN.

Of the atmospheric carbon reservoir species, methane is by far the largest. It may be noted that even considering only the atmosphere, Titan's area density of carbon is huge compared

TABLE 1. Size of carbon reservoirs on Titan (kg m⁻²).*

	CH ₄	C ₂ H ₆	C ₂ H ₂	HCN	Tholin	Non-C
Stratosphere	200	0.05	0.01	0.001	0.001	11 000
Troposphere	2300	0.02	neg	neg	neg	120 000
Ocean (50% CH ₄) (per 100 m depth)	20 000	20 000	30	0.27	–	~10 000
Sludge (per m depth)	–	800	–	800	–	–

*The tholin abundance ("neg" denotes negligible, – = not applicable) may underestimate the total mass production of haze by a factor of ~5, since some HCN and C₂H₂ may accrete onto haze particles as they descend. These reservoirs (apart from the ocean HCN and the heavier compounds in the stratosphere) are all considerably larger than the exchanging terrestrial carbon reservoirs with only a few kilograms per square meter.

with that of the Earth (compare Table 1 with the terrestrial values in section "Carbon-14 on Earth")

DESTRUCTION AND EXCHANGE TIMESCALES

Methane in Titan's atmosphere is not static but is exchanged and destroyed on various timescales. On geologic timescales, methane is converted to higher hydrocarbons in the stratosphere by solar ultraviolet radiation primarily, and energetic particles secondarily, and the hydrogen is lost to space. Therefore, this process is irreversible, the products are deposited on the surface, and methane must be renewed from a fresh source. The timescale for destruction of all of the methane currently in the atmosphere is roughly a few tens of millions of years (Yung *et al.*, 1984; Lara *et al.*, 1996; Toublanc *et al.*, 1995).

Evidently methane is resupplied to the atmosphere to counter photolytic loss, otherwise we should not see methane in Titan's atmosphere today. If methane is supplied from the deep interior, in the form of cryovolcanic eruptions, or from external sources such as comets, then the new methane has not interacted with the stratospheric methane currently undergoing photolysis. If, on the other hand, resupply is from a surface liquid reservoir of methane (along with photolytic products such as ethane) (Lunine *et al.*, 1983), then this material will freely exchange with tropospheric methane on very short timescales because of vapor pressure equilibrium. Assuming the surface liquid reservoir and the tropospheric reservoir to be each well-mixed, the timescale of interaction between the two is give approximately by the timescale to reach vapor pressure equilibrium should a perturbation occur. This in turn is the square of the boundary layer height divided by the effusion flux dP/c (pressure differential over the sound speed). A maximum value for the effusion flux is the methane partial pressure (0.1 bars) divided by c (equivalent to flow into a vacuum). Since the boundary layer height is of order centimeters, the minimum equilibration time is seconds. The maximum equilibration time is set by the minimum pressure perturbation, but as the pressure perturbation

declines, so does the amount of material exchanged. Hence, we can simply conclude that a surface reservoir will be in equilibrium with the lower troposphere on geologically short timescales.

The troposphere is the well-mixed region of the atmosphere, but methane in the troposphere must be transported to the stratosphere in order to be photolyzed. This exchange timescale can be derived from the eddy mixing coefficient K in the lower stratosphere in turn derived from photochemical models. We take $K \approx 10^3$ cm²/s, the lowest eddy diffusion coefficient used in the various photochemical models (Lara *et al.*, 1996; Yung *et al.*, 1984; *etc.*) at the tropopause, which yields a mixing time $H^2/K = 4 \times 10^9$ s, where H is the scale height (20 km). This maximum mixing time of ~100 years is much shorter than the photochemical or ¹⁴C enrichment timescales discussed above.

Higher K values, and the inclusion of any other processes, such as transport of methane to the stratosphere by moist convection, will only decrease the timescale. Thus, methane is well mixed among surface, tropospheric, and stratospheric reservoirs.

Microphysical models of the haze (Toon *et al.*, 1992) suggest that the haze particles take around 100–1000 years from production high in the atmosphere to removal by rainout at an altitude between about 60 and 80 km. Rainout is assumed to be rapid (canonically 1 year in models, but in fact simply fast enough that the residence can be ignored.)

RESULTANT CARBON-14 ABUNDANCES

A production rate of 9 atoms/cm²/s is assumed, corresponding to 5.4×10^{-14} kg/m²/year. Equating this production to the decay rate with the decay constant $\lambda = 1.24 \times 10^{-4}$ year⁻¹, this production rate yields an equilibrium ¹⁴C concentration of 3.7×10^{-11} kg m⁻². The intrinsic activity (decays per unit time per unit mass) depends on the reservoir into which the radiocarbon is dispersed (see Fig. 3).

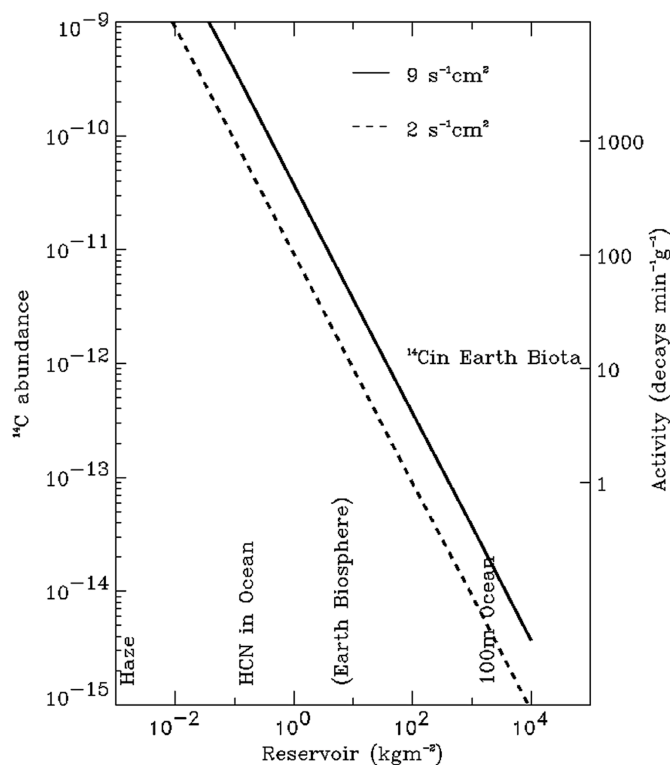


FIG. 3. Plot of the radiocarbon content as a function of the dilution reservoir, for terrestrial and estimated Titan production rates. The "fresh" count rate for terrestrial carbon is shown. If the dilution reservoir on Titan is small (*e.g.*, the haze) count rates could be very high.

If diluted in, for example, the stratospheric methane inventory, the ^{14}C concentration is $\sim 10^{-13}$, lower than the concentration on Earth (where the exchanging carbon inventory for dilution is much smaller). If diluted in the atmosphere as a whole, it is another factor of 10 less. And finally, if the ocean-troposphere exchange time is as small as 400 years (*i.e.*, a fraction of the half-life) the dilution reservoir is so large that the ^{14}C concentration would drop to undetectable levels. Similarly, if radiocarbon is primarily produced as ethane, there is no exchange as such—the ethane gets dumped in the ocean and is diluted into nondetection. However, methane and ethane seem among the less likely ^{14}C products.

If HCN is the main ^{14}C product, and is not incorporated into the haze, it would presumably be diluted in the ocean (undetectably for the bulk ocean, but if HCN liquid could be isolated in an instrument, the radiocarbon content in that species could be measurable).

If ^{14}C is incorporated into the haze, either directly or *via* HCN, the reservoir is potentially quite small. 100–1000 years-worth of ^{14}C production (*i.e.*, 10^{-11} kg/m 2) makes a sizeable fraction (several parts per billion) of the haze. Such material would see many thousand decays per minute per gram of material—comparable with radioactive ores on Earth, and

several orders of magnitude more radioactive than brazil nuts (the most radioactive terrestrial food, largely by incorporation of radium). Such activity may be significant in that it may modify the charge distribution on the particles—this may in turn affect the haze particle's coagulation and shape. The charge per particle is an important parameter in microphysical models of the haze, and ESA's Huygens probe carries instrumentation as part of the Huygens Atmospheric Structure Instrument (HASI) to measure atmospheric electrical properties.

By the time tholin haze reaches the surface, it has probably also accreted rather more abundant acetylene polymers and ice, so would be gram per gram less radioactive than tholin-only haze at high altitudes, dividing the radiocarbon production rate by the acetylene production rate still leaves a radiocarbon concentration of $\sim 10^{-9}$ and thus "fresh" material on Titan's surface will have a high intrinsic radioactivity.

The shielding of 150 keV electrons can be characterized by the "continuous slowing down approach" (CSDA) range which is approximately the average path length travelled by the particle before it comes to rest, perhaps a slightly more intuitive parameter than its reciprocal, k . The range was determined from the National Institute of Standards ESTAR code. The range (expressed as a mass per unit area) in sea level air is 0.03 g cm $^{-2}$, or 30 cm, or ~ 5 cm in Titan's atmosphere. In organic liquids like N-heptane (and by analogy liquid ethane, with a similar mass density of 0.6 g cm $^{-3}$) the range is 0.025 g cm $^{-2}$, or ~ 0.4 mm. In amorphous carbon with a density of 2 g cm $^{-3}$ (presumably a reasonable tholin analog) the range is 0.032 g cm $^{-2}$, or a range of ~ 150 μm . Even if the radiocarbon is diluted not just in tholin, but by the full acetylene production too (amounting to $\sim 10^{-5}$ kg m $^{-2}$ year $^{-1}$, or 10 nm/year) self-shielding can be neglected and in principle the measured surface decay rate should be close to the production rate of 9 cm $^{-2}$ s $^{-1}$.

IMPLICATIONS FOR HUYGENS

As indicated above, radiocarbon may modify the charging properties of the haze—models (*e.g.*, Borucki *et al.*, 1987) suggest each haze particle (a fraction of a micron across) may have a few tens of electrons charge. The production of an ion pair in nitrogen (and therefore air on Titan and Earth) requires only 35 eV, and so one 158 keV radiocarbon decay can produce several thousand electrons, penetrating a few centimeters in sea-level air. Optical and electrical measurements of the haze by the Huygens probe may constrain haze coagulation to the point where this effect may need to be taken into account.

Unfortunately, the sensitivity of the gas chromatograph-mass spectrometer on the probe will not be adequate to measure parts per billion isotope levels, so direct detection of radiocarbon will not be possible.

One significant effect we predict, however, is that the near-surface atmospheric ion density will be exceptionally high. Figure 1 shows that the ionization due to cosmic rays falls steeply near the surface, since most cosmic rays have already

been absorbed at high altitude. If the radiocarbon-bearing haze sediments out of the atmosphere on timescales short compared with the half-life (as models suggest it does), then haze deposits on dry land will produce decays at approximately the production rate of $9 \text{ cm}^{-2} \text{ s}^{-1}$ (regardless of how much the radiocarbon and tholin is diluted by HCN and acetylene ices and polymers). This decay rate is capable of producing some 10^4 cm^{-2} ion pairs, which will cause a strong increase in the air conductivity in the lowest part of the atmosphere (10^4 cm^{-2} exceeds the integrated GCR production for the lowest kilometer or so). The Huygens Atmospheric Structure Instrument (HASI; Fulchignoni *et al.*, 1997) has relaxation and mutual impedance sensors capable of measuring electron and ion conductivities. Even though the absolute ion abundances will depend on the (at present somewhat uncertain) recombination rate, an increase in near-surface ion abundance will be quite obvious in the data and difficult to explain otherwise.

If the probe lands in an ethane lake, the local radiocarbon will be suspended in the ocean and thus shielded from the atmosphere and no radioactive ionization would be expected (and seaspray generation or other such processes may in any case influence the atmosphere conductivity).

INSTRUMENTATION FOR FUTURE MISSIONS

In terrestrial laboratories ^{14}C is measured by either decay counting (Taylor, 1987) or by accelerator mass spectrometry (AMS). Most samples are measured by AMS which has much smaller sample requirements than decay counting (Fifield, 1999). Several designs exist for small, low-level gas-proportional counters, and the volumes of the counters can be ~ 5 to 100 mL. Currie *et al.* (1983) and Otlet *et al.* (1983), for example, discuss the use of low-background counting systems.

Another method for counting ^{14}C is liquid-scintillation counting. In this case, a scintillant is added to a liquid such as benzene. The β -particles interact with the scintillant to produce photons, which can be easily counted using photomultipliers. This method usually requires ~ 0.2 to 5 g C (Taylor, 1987).

In this section we consider briefly instrumentation to evaluate the radiocarbon content in several different reservoirs. We consider *in situ* instrumentation only, although we note that it is just conceivable that very sensitive millimeter or microwave spectroscopy could determine gas-phase abundances of radiocarbon isotopes of spectroscopically-active compounds like HCN from orbit.

One of the simplest instruments would be a radiation detector in a collection chamber. We consider a cell of 200 mL as a typical size. Gas is pumped in (or out) and the temperature of the cell may be controlled. It should be possible to incorporate some type of gas-proportional counter into such a system. Low-level counting systems using small gas counters with volumes as small as 10–30 mL were developed in the early 1980s (Currie *et al.*, 1983; Otlet *et al.*, 1983)

If the atmosphere is considered as a binary mixture of methane and nitrogen, the composition can be measured with some very simple and compact techniques (*e.g.*, speed of sound to give relative molecular mass, or optically-sensed near-infrared absorption by methane). The count-rate from the gas-proportional counter can determine count rate of ^{14}C and given the sample carbon mass we can determine ^{14}C activity. Concentration techniques such as compression, distillation or selective adsorption could also be applied.

An ocean analyzer would be similar in almost every respect to the gas analyzer. Similar distillation procedures could be applied to enrich a sample in involatile components such as ethane and HCN and remove methane and nitrogen, although some ancillary instrumentation would be required to determine the molecular composition and thus the bulk carbon content.

If the ^{14}C is produced as HCN and is incorporated into the ocean as a liquid (rather than turning into haze) then HCN extracted from the ocean would be quite radioactive as the HCN reservoir is quite small— 0.27 kg m^{-2} , see Fig. 3. (The small reservoir is because over geological timescales—far longer than ^{14}C lifetime—HCN is removed by precipitation from the ocean. Since C_2H_6 is not so removed, the dilution reservoir of that species is very large.)

Perhaps most challenging would be to measure the ^{14}C content of the suspended aerosol. This can only be accomplished by concentrating the aerosol in a collector, since the haze is so disperse (the optical thickness of Titan's haze is due not to high number density of haze particles, but due to the long pathlength through the vertically-extended atmosphere). Such a collector might use a porous metallic filter onto which aerosol material is impacted by airflow induced by a pump: such a technique is to be used on the aerosol collector and pyrolyzer instrument (ACP) on the Huygens probe

The ACP is expected to acquire a sample of a few tens of micrograms during the ~ 2 h Huygens probe descent. Some Titan exploration platforms might be able to collect haze material from high altitudes for longer periods or fly faster and so acquire larger sample masses. However, if haze is indeed the main ^{14}C sink, even a few tens of microgram sample will have a count rate of several counts per minute. The ^{14}C activity in a thin film of the aerosol, collected on a filter, could be counted using a photomultiplier with an attached thin solid scintillant, such as anthracene. Commercial designs for such equipment exist and are already used for counting radioactivities in air filters and similar samples. If the local radiation background is sufficiently low, as we expect, then it should be possible to detect ^{14}C in such aerosols using a similar device.

As for the surface, arbitrarily elaborate sampling arms, drills *etc.* maybe envisaged to introduce samples into some cavity sensor. Another possibility would be to insert a counter into soft deposits and record the count rates at different depths. However, note that even a 1 cm layer of material would be 2 Ma at its base, if the $10^{-14} \text{ g/cm}^2/\text{s}$ production rate of haze is assumed. One simple approach might be to mount a flat radiation sensor

on, for example, a footpad or other surface that is applied to the surface: this would readily indicate whether the surface has "fresh" haze on it.

CONCLUSIONS

We have considered the production and fate of radiocarbon on Titan, and find that the production per unit area may be $\sim 4\times$ that on Earth. Radiocarbon may also act as a useful tracer of photochemical and transport processes. We suggest that radiocarbon may most likely be incorporated into Titan's organic haze, either by physical attachment or *via* HCN and acetylene and their polymers. The haze in the atmosphere would therefore be quite radioactive and this may affect charging of the haze particles.

Similarly, haze material deposited on the surface on short timescales will render the upper tens of microns of the surface detectably radioactive. This may lead to an enhancement of near-surface atmospheric electrical conductivity over land, which may be detectable by the Huygens probe.

Absence of such activity implies either that radiocarbon is preferentially produced as another species (*e.g.*, ethane or methane, diluted undetectably in lakes and seas) or that haze material has not been recently deposited, or has been recently removed, from a surface. Surface radioactivity measurements on a mobile, probably aerial, platform on a future mission would therefore be a useful and simple constraint on erosive and depositional processes, which are likely to vary in intensity with, for example, latitude and altitude.

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